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Astrophysical axion bounds: An update

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Abstract.
The observed properties of stars and especially the neutrino signal of the supernova 1987A provide an upper limit to the axion mass, while the age and expansion rate of the universe provide a lower limit. There remains a "window of opportunity" $10^{-5}\,\mathrm{eV} \lesssim m_a \lesssim 10^{-2}\,\mathrm{eV}$, with large uncertainties on either side, where axions could still exist and where they would provide a significant fraction or all of the cosmic dark matter. The current status of this axion window is reviewed.

1. Introduction

The interest in axions as a possible dark matter candidate has recently soared thanks to the heroic experimental progress which has led to full-scale searches for galactic axions in Livermore [1] and Kyoto [2] which may well turn up dark matter axions within the next few years (Fig. 1). There is also a noteworthy axion search program in Novosibirsk [3].

For such efforts to make sense one needs to understand the "window of opportunity" where axions are not excluded by astrophysical and cosmological arguments. It is well known that the requirement that stars not lose too much energy by axions leads to a lower limit on the Peccei-Quinn scale f_a which can be translated into an upper limit on the axion mass by virtue of the relationship $m_a = 0.62\,\mathrm{eV}\,(10^7\,\mathrm{GeV}/f_a)$. It is also well known that the non-thermal production in the early universe leads to an upper bound on f_a (lower bound on m_a) lest axions "overclose" the universe. These topics are well-covered in a number of reviews [4] and books [5, 6]. Some recent refinements, however, justify the present update.

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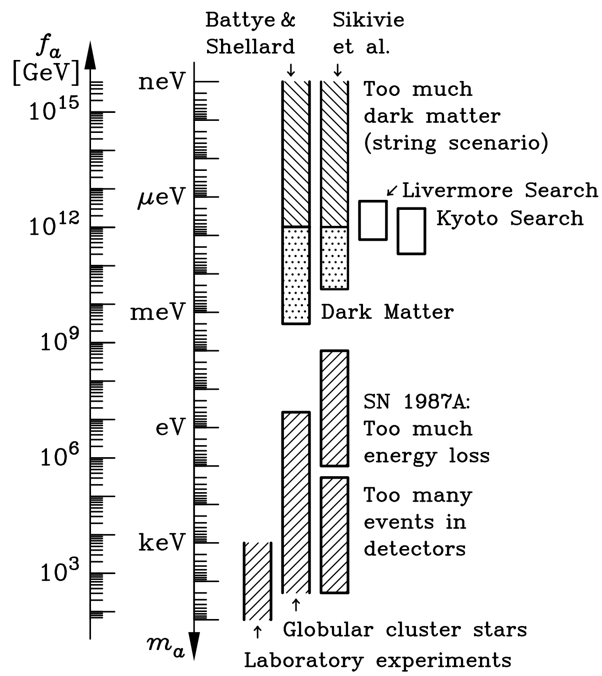

Figure 1. Summary of astrophysical and cosmological axion bounds. The globular cluster limit assumes an axion-photon coupling corresponding to $E/N = 8/3$ as in GUT models.

2. Stellar Limits

2.1. Globular Cluster Stars

In analogy to neutral pions, axions generically interact with photons according to $\mathcal{L}_{a\gamma} = g_{a\gamma}\mathbf{E}\cdot\mathbf{B}\,a$ with $g_{a\gamma} = (\alpha/2\pi f_a)\,(E/N - 1.92 \pm 0.08)$. The parameter E/N is a model-dependent fraction of small integers. This coupling allows for the axion decay $a \to 2\gamma$ as well as for the Primakoff conversion $a \leftrightarrow \gamma$ in the presence of external electromagnetic fields. Because charged particles and photons are abundant in the interior of stars they are powerful axion sources.

A novel energy-loss mechanism would accelerate the consumption of nuclear fuel in stars and thus shorten their lifetimes. A case where axion emission would be efficient and the stellar lifetime is well established are low-mass helium-burning stars, so-called horizontal-branch (HB) stars. Low-mass red giants have a degenerate helium core ($\rho \approx 10^6\,\mathrm{g\,cm^{-3}}$, $T \approx 10^8\,\mathrm{K}$) so that axion emission is strongly suppressed relative to the

cores of HB stars ($\rho \approx 10^4\,\mathrm{g\,cm^{-3}}$, $T \approx 10^8\,\mathrm{K}$) whence the number ratio of these stars in globular clusters is a sensitive measure for the operation of axionic energy losses. The observed number ratios agree with standard theoretical expectations to within a few tens of percent implying a limit [6] $g_{a\gamma} \lesssim 0.6\times10^{-10}\,\mathrm{GeV}^{-1}$. In GUT axion models where $E/N = 8/3$ this yields $m_a \lesssim 0.4\,\mathrm{eV}$ (Fig. 1). Our often-quoted "red giant limit" is less restrictive because it was based on the statistically less significant number of "clump giants" in open clusters [7].

2.2. Supernova 1987A

Being a QCD phenomenon, axions a generically also couple to nucleons N by $(C_N/2f_a)\overline{\psi}_N\gamma_\mu\gamma_5\psi_N\partial^\mu a$ where the C_N for protons and neutrons are model-dependent numerical coefficients. The most significant limit on the axion-nucleon coupling arises from the cooling speed of nascent neutron stars as established by the duration of the neutrino signal from the supernova (SN) 1987A.

Apart from the well-known overall uncertainty of this argument caused by the statistical weakness of only 19 observed neutrinos there is a problem related to the axion emission rate from the hot and dense nuclear medium. In a naive perturbative picture this rate is computed as a bremsstrahlung process $NN \to NNa$ with the nucleons interacting by a spin-dependent force. The resulting nucleon spin fluctuations act as a source for the emission of axions. Like any other bremsstrahlung process, this rate scales with the density as ρ^2. However, if one studies axion emission from the more general perspective of linear response theory it turns out that the ρ^2 scaling is not maintained to arbitrary densities. Rather, the axion emission rate does not exceed a certain limit which can be estimated from sum rules of the spin-density dynamical structure functions [8, 9]. While a detailed calculation of these structure functions is not available, simple estimates indicate that in a SN core one is well in the saturation regime of the bremsstrahlung process. The previous naive emission rate is thus reduced by about an order of magnitude.

Moreover, a previous often-quoted limit [10] of $m_a \lesssim 1\,\mathrm{meV}$ was based on the generic coupling constants $C_N = 0.5$ for both protons and neutrons. In realistic axion models these couplings can be much smaller. For example, in the popular KSVZ model which is representative for the class of hadronic axion models the interaction with neutrons nearly vanishes. Altogether the SN 1987A limit is reduced to roughly $m_a \lesssim 10\,\mathrm{meV}$ [8]. Inevitably this limit involves large uncertainties which are difficult to quantify.

Most recently the SN 1987A axion limit was reexamined in a series of numerical cooling calculations where the saturation effect was included and the coupling constants to neutrons and protons were chosen appropriately

for specific models [11]. For KSVZ axions the limit was found to be about 8 meV, in perfect agreement with the simple estimate of Ref. [8]. For DFSZ axions the limit varies between about 4 and 12 meV, depending on the assumed value of the angle β which measures the ratio of two Higgs vacuum expectation values. Because this angle is not known one can only use the least restrictive number as a conservative limit. In view of the large overall uncertainties it is good enough to remember $m_a \lesssim 10\,\mathrm{meV}$ as the current SN 1987A limit for both KSVZ and DFSZ axions.

If axions interact too strongly they are trapped and contribute to the transfer of energy rather than to a direct cooling of the inner SN core. Therefore, axions with $m_a \gtrsim 10\,\mathrm{eV}$ cannot be excluded on the basis of the duration of the SN 1987A neutrino signal [12].

However, axions with masses larger than this, i.e., with stronger interactions, could actually cause a significant contribution to the signal measured in the IMB and Kamiokande II water Cherenkov detectors by the absorption on $^{16}\mathrm{O}$ and the subsequent emission of γ rays. To avoid too many events one can exclude the range $20\,\mathrm{eV} \lesssim m_a \lesssim 20\,\mathrm{keV}$ [13].

2.3. White Dwarf Cooling

In certain models axions couple to electrons by $(C_e/2f_a)\overline{\psi}_e\gamma_\mu\gamma_5\psi_e\partial^\mu a$ with C_e a model-dependent factor of order unity. For most purposes this derivative coupling is equivalent to the pseudoscalar structure $-ig_{ae}\overline{\psi}_e\gamma_5\psi_e a$ with the Yukawa coupling $g_{ae} = C_e m_e/f_a$ which one may parametrize by $\alpha_{26} \equiv (g_{ae}^2/4\pi)/10^{-26}$.

It was suggested that axion emission with $\alpha_{26} \approx 0.45$ might dominate the cooling of white dwarfs such as the ZZ Ceti star G117–B15A for which the cooling speed has been established by a direct measurement of the decrease of its pulsation period [14]. Because of this suggestion a new bound on α_{26} was derived by a method similar to the above number counts in globular clusters [15]. The resulting limit $\alpha_{26} \lesssim 0.5$ is the best direct bound on the axion-electron coupling, but it does not quite exclude the possibility that axions could play a certain role in white dwarf cooling.

The most popular example where axions couple to electrons is the DFSZ model where $C_e = \frac{1}{3}\cos^2\beta$ with β an arbitrary angle. In this case one may use the SN 1987A limits on the axion-nucleon coupling to derive an indirect β-dependent limit on the axion-electron coupling. In this way I infer from Ref. [11] that the largest axion-electron coupling allowed by SN 1987A corresponds to $\alpha_{26} \approx 0.08$. For typical parameters of old white dwarfs the axion luminosity is $0.7\,\alpha_{26}$ times their photon luminosity [6]. Therefore, DFSZ axions do not seem to be able to play a significant role in the cooling of old white dwarfs. (A novel cooling mechanism may be required if the microlensing events of the MACHO collaboration are to be interpreted

as halo white dwarfs [16].) However, axion cooling may be important in strongly magnetized white dwarfs where the cyclotron process provides for an additional emission channel [17].

3. Mass of Dark Matter Axions

If axions interacted sufficiently strongly ($f_a \lesssim 10^8\,\mathrm{GeV}$) they would have come into thermal equilibrium before the QCD phase transition, leading to a background sea of invisible axions in analogy to the one expected for neutrinos [18]. This parameter range is excluded by the astrophysical arguments summarized in Fig. 1 which imply that axions interact so weakly that they have never come into thermal equilibrium. Still, the well-known misalignment mechanism will excite coherent oscillations of the axion field [19]. In units of the cosmic critical density one finds for the axionic mass density

$$\Omega_a h^2 \approx 1.9 \times 4^{\pm 1} (\mu\mathrm{eV}/m_a)^{1.175}\, \Theta_i^2\, F(\Theta_i) \qquad (1)$$

where h is the present-day Hubble expansion parameter in units of $100\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. The stated range reflects recognized uncertainties of the cosmic conditions at the QCD phase transition and uncertainties in the calculation of the temperature-dependent axion mass. The cosmic axion density depends on the initial misalignment angle Θ_i which could lie anywhere between 0 and π. The function $F(\Theta)$ encapsules anharmonic corrections to the axion potential; for an analytic determination see Ref. [20].

If Θ_i is of order unity, axions with $m_a = \mathcal{O}(1\,\mu\mathrm{eV})$ provide roughly the cosmic closure density. The equivalent Peccei-Quinn scale $f_a = \mathcal{O}(10^{12}\,\mathrm{GeV})$ is far below the GUT scale so that one may speculate that cosmic inflation, if it occurred at all, did not occur after the PQ phase transition. If it did not occur at all, or if it did occur before the PQ transition with $T_{\mathrm{reheat}} > f_a$, the axion field will start with a different Θ_i in each region which is causally connected at $T \approx f_a$. Then one has to average over all regions to obtain the present-day axion density.

More importantly, because axions are the Nambu-Goldstone mode of a complex Higgs field after the spontaneous breaking of a global U(1) symmetry, cosmic axion strings will form by the Kibble mechanism [21]. The motion of these global strings is damped primarily by the emission of axions rather than gravitational waves. At the QCD phase transition the U(1) symmetry is explicitly broken (axions acquire a mass) causing domain walls bounded by strings to form which get sliced up by the interaction with strings. The whole string and domain-wall system will quickly decay into axions. This complicated sequence of events leads to the production of the dominant contribution of cosmic axions. Most of them are produced near the QCD transition at $T \approx \Lambda_{\mathrm{QCD}} \approx 200\,\mathrm{MeV}$. After they acquire a

mass they are nonrelativistic or mildly relativistic so that they are quickly redshifted to nonrelativistic velocities. Thus, the string and domain-wall produced axions form a cold dark matter component.

In their recent treatment of axion radiation from global strings, Battye and Shellard [23] found that the dominant source of axion radiation are string loops rather than long strings, contrary to what had been assumed in the previous works by Davis [21] and Davis and Shellard [22]. At a given cosmic time t the average loop creation size is parametrized as $\langle \ell \rangle = \alpha t$ while the radiation power from loops is $P = \kappa\mu$ with μ the renormalized string tension. The loop contribution to the cosmic axion density is [23]

$$\Omega_a h^2 \approx 88 \times 4^{\pm 1} \left[(1+\alpha/\kappa)^{3/2} - 1 \right] (\mu\mathrm{eV}/m_a)^{1.175}, \qquad (2)$$

where the overall uncertainty has the same source as before. The exact values of the parameters α and κ are not known; Battye and Shellard expect $0.1 < \alpha/\kappa < 1.0$. The expression in square brackets is then between 0.15 and 1.83.

The proper treatment of axion radiation by global strings has been controversial. Sikivie and his collaborators [24] have consistently argued that the motion of global strings was overdamped, leading to an axion spectrum emitted from strings or loops with a flat frequency spectrum. In Battye and Shellard's treatment, wavelengths corresponding to the loop size are strongly peaked; the motion is not overdamped. In Sikivie et al.'s picture much more of the string-radiated energy goes into kinetic axion energy which is redshifted so that ultimately there are fewer axions. The cosmic axion density is then of order the misalignment contribution.

If axions are the dark matter of the universe one may estimate $0.08 < \Omega_a h^2 < 0.40$. I have assumed that the universe is older than 10 Gyr, that the total matter density is dominated by axions with $0.3 < \Omega_{\mathrm{matter}} < 1$, and that $0.5 < h < 1.0$. Including all of the previously discussed uncertainties I arrive at a plausible mass range for dark-matter axions of

$$m_a = \begin{cases} 6\text{–}250\ \mu\mathrm{eV} & \text{Sikivie et al.,} \\ 6\text{–}2000\ \mu\mathrm{eV} & \text{Battye and Shellard,} \end{cases} \qquad (3)$$

as indicated in Fig. 1. Even though Battye and Shellard tend to favor larger axion masses for the dark matter, the treatments of both groups imply the same lower end for the plausible range. Evidently, the Livermore and Kyoto search experiments cover a large fraction of the predicted range, even though it would be desirable to extend the search to even larger masses.

4. Phase Space Distribution

The galactic phase-space distribution of axions may well exhibit novel features which are of relevance for the search experiments. Different initial

misalignment angles in different causally connected regions lead to density fluctuations which are nonlinear from the start. This leads to the formation of "axion mini clusters" which may partially survive galaxy formation and thus can be found in the Milky Way today [25]. For a suitably large initial density contrast these clusters can condense into axionic boson stars by virtue of higher order axion-axion couplings and may be detectable by the femtolensing effect [26]. The direct search experiments need sufficient sensitivity to pick up the diffuse component of the galactic axions which are not locked up in mini clusters.

Another interesting possibility is that axions may have maintained some of their initial phase-space distribution, i.e. that they are not fully virialized in the galaxy. In this case the axion velocity distribution would exhibit very narrow peaks which could enhance the sensitivity of the direct search experiments and in any case may be detectable in the laboratory [27].

5. Summary

After some refinements and corrections, the astrophysical and cosmological axion limits seem to have stabilized to what is shown in Fig. 1. There remains a "window of opportunity" $10^{-5}\,\mathrm{eV} \lesssim m_a \lesssim 10^{-2}\,\mathrm{eV}$ where axions could still exist. They would then contribute most or all of the dark matter of the universe. The ongoing direct search experiments for galactic axions have reached a sensitivity where they are in a position to confirm this bold hypothesis or to refute it.

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